Single- and Double-Pion Production in Nucleon Collisions on the Nucleon and on Nuclei – the ABC Effect and its Possible Origin in a Dibaryonic Resonance

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Abstract

The ABC effect – an intriguing low-mass enhancement in the $\pi\pi$ invariant mass spectrum – is known from inclusive measurements of two-pion production in nuclear fusion reactions. First exclusive measurements carried out at CELSIUS-WASA for the fusion reactions leading to d or ^{3}He reveal this effect to be a σ channel phenomenon associated with the formation of a $\Delta\Delta$ system in the intermediate state and combined with a resonance-like behavior in the total cross section. Together with the observation that the differential distributions do not change in shape over the resonance region the features fulfill the criteria of an isoscalar s-channel resonance in pn and $NN\pi\pi$ systems, if the two emitted nucleons are bound. It obviously is robust enough to survive in nuclei as a dibaryonic resonance configuration. In this context also the phenomenon of $N\Delta$ resonances is reexamined.

1 Introduction

The ABC effect – first observed by Abashian, Booth and Crowe [1] in the double pionic fusion of deuterons and protons to ^{3}He – stands for an unexpected enhancement at low masses in the spectrum of the invariant $\pi\pi$-mass $M_{\pi\pi}$. Follow-up experiments [2, 3, 4, 5, 6, 7, 8, 9, 10, 11] revealed this effect to be of isoscalar nature and to show up in cases, when the two-pion production process leads to a bound nuclear system. With the exception of low-statistics bubble-chamber measurements [4, 8] all experiments conducted on this issue have been inclusive measurements carried out preferentially with single-arm magnetic spectrographs for the detection of the fused nuclei.

Initially the low-mass enhancement had been interpreted as due to an unusually large $\pi\pi$ scattering length and as evidence for the σ meson, respectively [1]. Since the effect showed up particularly clearly at beam energies corresponding to the excitation of two Δs in the nuclear system, the ABC effect was

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interpreted lateron by a $\Delta\Delta$ excitation in the course of the reaction process leading to both a low-mass and a high-mass enhancement in isoscalar $M_{\pi\pi}$ spectra [12, 13, 14, 15, 16]. In fact, the missing momentum spectra from inclusive measurements have been in support of such predictions. It has been shown [17] that these structures can be enhanced considerably in theoretical calculations by including ρ exchange and short-range correlations.

2 Experiment

In order to shed more light on this issue, exclusive measurements of the reactions $pd \to pd\pi^0\pi^0$ ($T_p = 1.03$ and 1.35 GeV) and $pd \to {}^3$He$\pi\pi$ ($T_p = 0.893$ GeV) have been carried out in the energy region of the ABC effect at CELSIUS using the 4π WASA detector setup with pellet target system [18]. The selected energies have been close to the maximum of the ABC effect observed in the respective inclusive measurements. The $pd \to pd\pi^0\pi^0$ reaction proceeds as quasifree $pn \to d\pi^0\pi^0$ reaction with a spectator proton of very small momentum in the lab system. Since all ejectiles with the exception of the spectator have been measured, the spectator momentum has been reconstructed by kinematical fits with three overconstraints. Preliminary results for the reaction can be found in recent conference proceedings [19, 20, 21, 22]. The experimental results on the $pd \to {}^3$He$\pi^0\pi^0$ and $pd \to {}^3$He$\pi^+\pi^-$ reactions have been published already in Ref. [23, 24].

3 Experimental Results

Some specific results of the CELSIUS-WASA measurements are shown in Figs. 1 and 2 for the double-pionic fusion to the deuteron, which is the most basic reaction for studying the ABC-effect. Fig. 1 depicts the spectra of the invariant masses $M_{\pi^0\pi^0}$ and $M_{d\pi^0}$ for the quasifree $pn \to d\pi^0\pi^0$ reaction at the beam energy $T_p = 1.03$ GeV [1] .

The $\pi^0\pi^0$ channel, which is free of any isospin I=1 contributions, exhibits a pronounced low-mass enhancement (ABC effect) in the $M_{\pi^0\pi^0}$ spectrum both in the fusion process to the deuteron and in the one leading to ^{3}He[23, 24]. We note that in the ^{3}He$\pi^+\pi^-$ channel the threshold enhancement is observed [23] too, however, less pronounced. The reason for this is that this channel in addition contains isovector contributions - as may be seen [25] by the small shifts between the Δ peaks in the $M_{{}^3\mathrm{He}\pi^+}$ and $M_{{}^3\mathrm{He}\pi^-}$ spectra – see Fig. 5 of Ref. [23]. However, the main result of these measurements is that indeed two Δs are excited simultaneously in this reaction – in support of the hypothesis that a $\Delta\Delta$ system is excited in the course of the double pionic fusion process.

From the measured angular distributions [20, 23, 24] we find the following features:

- The pion angular distribution in the $\pi\pi$ subsystem is flat for the low-mass enhancement region in the $M_{\pi\pi}$ spectrum, i.e., the ABC-effect is of scalar-isoscalar nature – in other words it is a σ channel phenomenon.

- The distribution of the opening angle between the two pions shows that the ABC-effect is associated with two pions leaving the interaction vertex in parallel.

- The angular distribution of the $\pi\pi$ system (which is aquivalent to the angular distribution of the residual nucleus) in the overall center-of-mass system is not flat. It rather corresponds to a double p-wave distribution as expected from the decay of the $\Delta\Delta$ system.

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[1] Note that due to Fermi motion of the nucleons in the target deuteron the quasifree reaction process proceeds via a continuum of effective collision energies in the range 0.94 - 1.18 GeV with according kinematical smearing in the differential distributions. This smearing may be reduced strongly by dividing the data into narrow bins of effective collision energy at the cost of statistics.
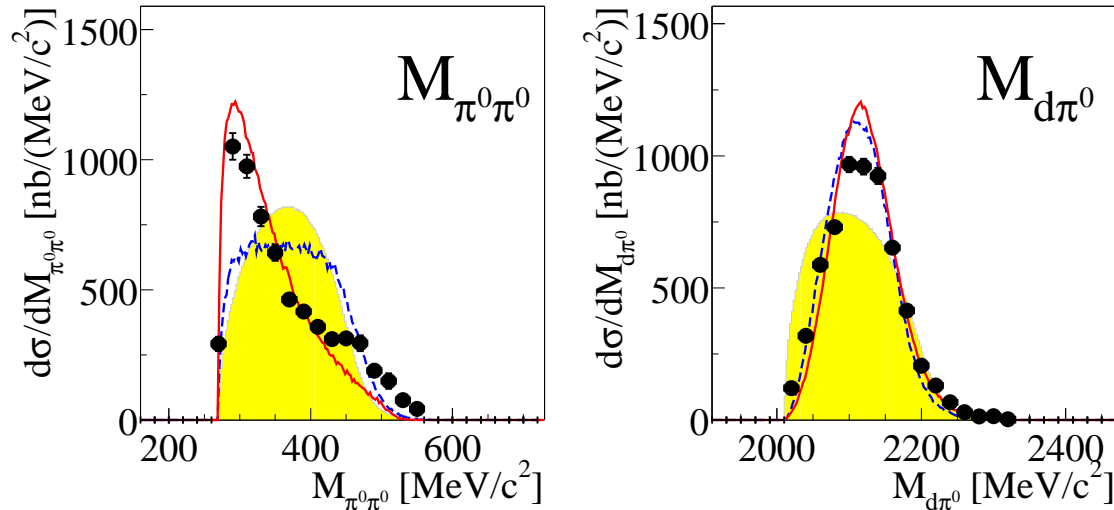
Figure 1: Distributions of the invariant masses $M_{\pi^0\pi^0}$ and $M_{d\pi^0}$ from the exclusive measurement of the quasifree $pn \rightarrow d\pi^0\pi^0$ reaction at a beam energy $T_p = 1.03$ GeV. The shaded areas show the pure phase space distributions. Solid and dashed curves give $\Delta\Delta$ calculations with and without the assumption of a quasibound state in the $\Delta\Delta$ system leading to a resonance in the pn and $d\pi^0\pi^0$ systems (from Ref. [20]).

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From the measurements of the quasifree $pn \rightarrow d\pi^0\pi^0$ reaction at various energies we notice that the differential distributions do not change in shape significantly with energy. This points to the dominance of a single partial wave in the entrance channel, as is the case for the excitation of a s-channel resonance. As a consequence of such an assumption we should find a resonance-like energy dependence in the total cross section. Actually this is what in fact is observed for this reaction. In Fig. 2 we show the energy dependence of the total cross section of the double-pionic fusion to the deuteron. Depicted are the results for the $pn \rightarrow d\pi^+\pi^-$ reaction from bubble chamber measurements at DESY [4] and JINR [8] together with the preliminary CELSIUS-WASA results [19, 20] for the quasifree $pn \rightarrow d\pi^0\pi^0$ reaction at two incident energies, which have been binned into narrow ranges of effective collision energy providing thus four entries below and two entries above the peak energy. Since $\pi^+\pi^-$ and $\pi^0\pi^0$ channels are related by an isospin factor of two, the $\pi^0\pi^0$ results are plotted in Fig. 2 multiplied by this isospin factor. A resonance-like behavior of the total cross section is obvious.

4 Discussion and Interpretation of Experimental Results

The $\pi\pi$ low-mass enhancements observed in the exclusive data for the $\pi^0\pi^0$ channels turn out to be much larger than predicted in previous $\Delta\Delta$ calculations[12, 14, 16]. As an example we show by the dashed lines in Fig.1 and by dotted lines in Fig. 2 calculations in the model ansatz of Ref. [12], where we additionally included the pion angular distribution in Δ decay and the Fermi smearing of the nucleons bound in the final nucleus. Contrary to these predictions the data also do not exhibit any high-mass enhancement in $M_{\pi^0\pi^0}$ that had been supported by the inclusive measurements, too. As suspected already in Ref. [9] the high-mass bump observed in inclusive spectra rather turns out to be associated with $\pi\pi\pi$ and η production as well as with I=1 contributions. Since on the one hand the available $\Delta\Delta$ calculations obviously fail, but on the other hand the data clearly show the $\Delta\Delta$ excitation in the $M_{N\pi}$ spectra, a profound physics piece appears to be missing. Such a missing piece may be provided by a
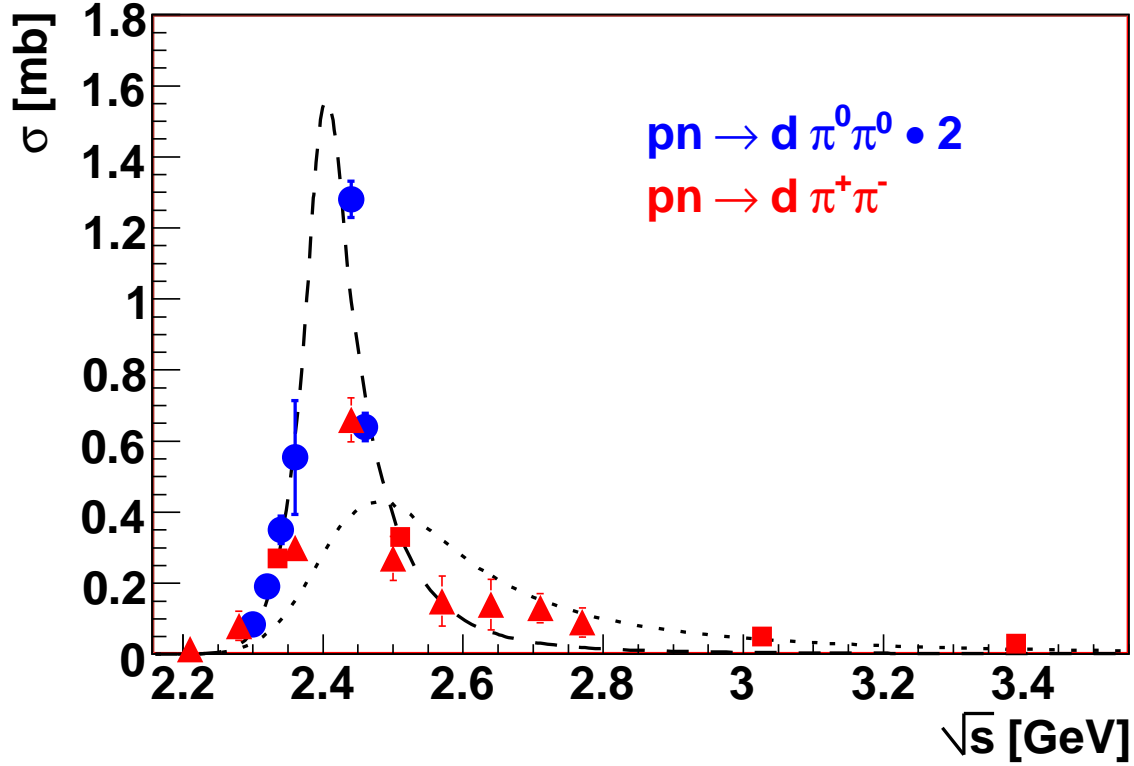
Figure 2: Energy dependence of the $pn \rightarrow d\pi\pi$ reaction with preliminary results of this work for the $\pi^0\pi^0$ channel (quasi-free measurements at two incident energies) and results for the $\pi^+\pi^-$ channel from Ref. [8](squares) and Fig. 2c of Ref. [4] (triangles). Dashed and dotted lines represent calculations with and without the assumption of a quasibound state in the $\Delta\Delta$ system leading to a resonance in the pn and $d\pi^0\pi^0$ systems.

strong $\Delta\Delta$ attraction or even a boundstate formation, as was demonstrated in Refs.[23, 24, 26, 27].

The essential clue to the nature of the ABC effect appears to be in the intriguing energy dependence of the double-pionic fusion in the isoscalar channel. We note that the isovector fusion channel $pp \rightarrow d\pi^+\pi^0$, shows **no** ABC effect [30] despite a clear $\Delta\Delta$ excitation signal in its differential spectra. It also exhibits an energy dependence [31] in its total cross section, which is close to the dotted curve in Fig. 2. In contrast the isoscalar fusion channel exhibits a much more pronounced energy-dependence in accordance with a resonance excitation having a width of roughly 100 MeV or even less, i.e. much smaller than twice the Δ width expected from usual $\Delta\Delta$ calculations. As also borne out by the data in Fig. 2 the cross section maximum at $\sqrt{s} \approx 2.4$ GeV means that the resonance mass is below twice the Δ mass, i.e. a quasibound state in the isoscalar $\Delta\Delta$ system, which not only can decay into the pn system, but also into the isoscalar $d\pi\pi$ system, because the Δ decay width is larger than the binding of this state.

In fact, if we use a Breit-Wigner term with a $q_{\Delta\Delta}$ dependent width and adjust the width parameters not to fit the total cross section data, but to reproduce the ABC-effect in the $M_{\pi^0\pi^0}$ spectra, then we obtain not only a quantitative description of all differential data (see, e. g., solid curves in Fig. 1) but at the same time also a quantitative description of the energy dependence of the total cross section (dashed curve in Fig. 2)thus obtaining automatically the observed width of the total cross section data.

Before proceeding here any further, we would like to discuss the experimentally necessary conditions

to establish a s-channel resonance. In case of a two-body reaction these may be given easily as follows:

- a resonance must be governed by a single partial wave and

- this partial wave must exhibit a resonant behavior in its real and imaginary amplitude parts leading to a pronounced looping in the Argand plot of this particular partial wave.

That way and by detailed partial wave analyses also resonances can be sensed, which in the observables are not seen directly, because they are burried underneath a background of other processes. Even in the case that a single partial wave contains also a lot of nonresonant contributions, a pole search in the complex plane of the partial-wave amplitude as well as an Argand plot can reveal hidden resonances – as is well known, e. g., from the study of the Roper resonance [32, 33].

If in a particular reaction excitation and decay of a resonance is the dominating process over a sufficiently large energy region, then the situation is much simpler:

- the total cross section must exhibit a Breit-Wigner like energy dependence and

- the angular distibution has to keep the same shape over the region of the resonance ("frozen distribution") being symmetric about $90°$ in the center-of-mass system.

4.1   Resonances in the $N\Delta$ system

In order to examine this situation on an example close to our problem, we reinvestigate the situation of $N\Delta$ resonances, which show up both in elastic pp and πd scattering, and, in particular, in the $pp \to d\pi^+$ reaction, which also has been measured over a wide energy range [34]. For all three reaction channels there are ample data in the region of interest. Also there exist detailed partial wave analyses for each of these reaction channels separately [34, 35, 36] as well as combined analyses [37]. Whereas elastic NN scattering couples to many channels and hence is quite insensitive to particular resonance states, elastic πd scattering and especially the reaction $pp \to d\pi^+$ select specifically single Δ excitations in two-body processes. The latter reaction has been investigated intensively at the pion factories LAMPF, TRIUMF and PSI via the reversed reaction $\pi^+ d \to pp$.

The data for the $pp \to d\pi^+$ reaction exhibit an energy dependence of the total cross section, which is in very close correspondence to a Breit-Wigner resonance peaking at $T_p \approx 550$ MeV and sitting on a very low background at higher energies. In addition the angular distibution, which has a $(3\ cos^2\Theta_{cm}+1)$ dependence – specific to Δ excitation and decay –, keeps its shape from a few MeV above threshold up to $T_p \approx 650$ MeV. I. e., this reaction shows already on a qualitative level all features of a s-channel resonance, which carries the characteristics of a single Δ excitation.

With such features in the data it is not surprising that their partial-wave analysis exhibits a clear resonant behavior in the partial waves ^1D_2P, ^3F_3D, ^3P_2D and ^1G_4F (in the notation $^{2S_{pp}+1}L_J^{pp}L^\pi$). All four partial waves describe textbook examples of a resonant behavior in real and imaginary parts of their amplitudes with close-to-perfect loopings in the Argand plot (see Figs. 7 and 8 of Ref. [34]). The by far dominating partial wave is ^1D_2P, which governs more than 90% of the total cross section up to $T_p \approx 500$ MeV (see Fig. 5 of Ref. [34]). At higher energies also the other three partial waves come into play. Their partial wave cross sections peak right at the $N\Delta$ mass of $\sqrt{s} = 2170$ MeV. The cross section of the ^1D_2P partial wave, however, peaks already at lower energy corresponding to $\sqrt{s} = 2130$ MeV. The resonant cross sections have a width of roughly 120 MeV, which conforms with the width of the Δ resonance. The special role of the $^1D_2$ partial wave has been already noted as early as 1968 by R. N. Arndt in his article about the "Unbound Diproton" [38]

All four partial waves represent resonant $N\Delta$ configurations. However, only ^1D_2P corresponds to a configuration, where the relative orbital angular momentum between N and Δ is zero. This explains its dominant role in this reaction. Also it is the only configuration, which resonates roughly 40 MeV

below the $N\Delta$ threshold. This means that the isovector s-wave interaction between N and Δ is strongly attractive with the ability to form a $I(J^P) = 1(2^+)$ state with a binding of about 40 MeV. Since the width of the Δ constituent in this state is larger than its binding energy, this state appears to be only quasi-bound. We note, however, that despite this binding the total width of this resonant state is obviously not significantly smaller than that of the free Δ resonance. This result will be of importance for the discussion of resonant states in the $\Delta\Delta$ system in the following paragraph.

We finally note that without the assumption of a s-channel resonance the experimental result for the angular distribution to coincide with that for Δ excitation and decay would not be easily understandable. In case of t-channel Δ excitation on one of the nucleons by meson exchange, the relevant reference axis for the polar angle of the pion emitted in Δ decay would be given by the momentum transfer $\vec{q}$ and not by the beam axis. Since the direction of $\vec{q}$ varies with the scattering angle, the resulting cms-angular distribution for the pions with the beam axis as the reference axis, would be smeared out yielding approximately a much flatter $(1 \cos^2\Theta_{cm} + 1)$ dependence.

4.2 Quasibound State in the $\Delta\Delta$ System

After the excursion to the $N\Delta$ system we come back to the discussion of the $\Delta\Delta$ system. We see that similar to the resonant ^3F_3D, ^3P_2D and ^1G_4F partial waves, which peak right at the $N\Delta$ threshold, the $\Delta\Delta$ excitation in the isovector channel $pp \to d\pi^+\pi^0$ peaks right at the $\Delta\Delta$ threshold as expected from a calculation of the $\Delta\Delta$ process without mutual interaction of the two Δs. Also the experimentally observed width of the resonance-like energy dependence of the total cross section coincides with the expected width of twice the Δ width.

The situation is different for the isoscalar channels $pn \to d\pi^+\pi^-$ and $pn \to d\pi^0\pi^0$, where the data suggest a peak postion near $\sqrt{s} = 2.41$ GeV, i. e. some 50 MeV below the $\Delta\Delta$ threshold. Here the situation is reminiscent of the ^1D_2P partial wave in case of the $N\Delta$ system. Also the resonance-like behavior in the total cross section and the observed "frozen distributions" in the differential cross sections fulfill the conditions of a s-channel resonance in these isoscalar channels. Note that with three particles in the exit channel there are now much more differential distributions than just the single angular distribution in case of only two ejectiles.

However, the big difference now is that we again observe a width in the resonant cross section of 100 MeV, which is, however, only half of that expected naively. In case of the ^1D_2P partial wave in the $N\Delta$ system the binding did not lead to a noticeable change of the decay width. Hence we conclude that the observed width in the isoscalar channel is obviously not just the simple result of the binding between the two Δ states. It rather signals more complicated configurations in the wave function of the intermediate state, which hinder its decay – as would be expected for a non-trivial dibaryon state.

Our model calculations for the quasibound state in the $\Delta\Delta$ system assume that the decay into the $\Delta\Delta$ system proceeds via relative s-waves between the two Δs. Since these calculations describe the measured angular distributions very well, we conclude that the spin-parity assignment to this isoscalar intermediate state should be either $J^P = 1^+$ or 3^+, where we take into account that the two-fermion system has to be in an antisymmetric state.

We note that the existence of such states has been predicted in different theoretical calculations [39, 40, 41] and sometimes [39] referred to as "inevitable dibaryon".

5 Conclusions and Outlook

The finding of a s-channel resonance in the isoscalar $pn \to d\pi\pi$ channel has the consequence that this resonance should show up also in the elastic pn scattering channel. Unfortunately in the corresponding energy region of $T_p = 1.0$ - 1.3 GeV such data are very sparse or non-existent, respectively. Moreover,

from the analysis of the $pn \to d\pi\pi$ data we expect the s-channel resonance to show up in pn elastic scattering with a peak cross section of several 100 μbarn only, which has to be compared with a total elastic pn cross section of about 20 mb in this energy region. I.e., only a detailed partial wave analysis of very precise elastic pn scattering data over the energy region $T_p = 1.0$ - 1.3 GeV would have the potential to sense this resonance in the $^3S_1$ and $^3D_3$ partial waves, respectively.

Another finding from the analysis of the $pn \to d\pi^0\pi^0$ data is that the ABC effect – a σ channel low-mass enhancement in the $M_{\pi\pi}$ spectra – is intimately connected to the appearence of the s-channel resonance in isoscalar pn and $\Delta\Delta$ systems. Since the ABC-effect shows up also in heavier nuclear systems, this means that this resonance is a quite stable object, which even survives in the nuclear surroundings. In fact, the energy dependence measured for the ^{3}He and ^{4}He cases in previous inclusive measurements [6] is in support of this conclusion.

The observed strong energy dependence of the $pn \to d\pi^0\pi^0$ reaction certainly needs further experimental verification. This is even more true for the energy dependencies observed for the double-pionic fusion reactions leading to ^{3}He and ^{4}He. Therefore we have proposed to investigate these energy dependencies in dedicated exclusive measurements at COSY using there the newly installed and upgraded WASA detector, which recently had been moved succesfully from the CELSIUS-ring at Uppsala to the COSY-ring at Forschungszentrum Jülich.

Acknowledgments

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